Modeling Energy Consumption in Single-Hop IEEE 802.11 Ad Hoc Networks

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***Abstract*— This paper presents an analytical model to predict energy consumption in saturated IEEE 802.11 single-hop ad hoc networks under ideal channel conditions. The model we introduce takes into account the different operational modes of the IEEE 802.11 DCF MAC, and is validated against packet-level simulations. In contrast to previous works that attempted to characterize the energy consumption of IEEE 802.11 cards in isolated, contention-free channels (i.e., single sender/receiver pair), this paper investigates the extreme opposite case, i.e., when nodes need to contend for channel access under saturation conditions. In such scenarios, our main findings include: (1) contrary to what most previous results indicate, the radio's *transmit* mode has marginal impact on overall energy consumption, while other modes (*receive, idle, etc.*) are responsible for most of the energy consumed; (2) the energy cost to transmit useful data increases almost linearly with the network size; and (3) transmitting large payloads is more energy efficient under saturation conditions.**

I. Introduction

Since most ad hoc networks include nodes that are connected to limited power sources (e.g., batteries), energy resources are considered precious. As a result, in the past few years, the design of "energy-efficient" or "energy-aware" protocols for ad hoc networks has become an area of intense research. Understanding the energy consumption at all network layers—as well as energy consumed resulting from inter-layer interactions—is a fundamental step in the design of power-efficient protocols for wireless ad hoc networks.

As it has already been reported in the literature [1], [2], energy consumption of a wireless network interface card (NIC) can be significant, especially when small, power-anemic devices are considered. Typically, NICs implement two layers of the protocol stack, namely the medium access control (MAC) and the physical (PHY) layers. Nowadays, most commercial wireless NICs are based on the IEEE 802.11 standard [3]. The IEEE 802.11 MAC (its distributed coordination function (DCF), in particular) is also widely available in many discrete-event network simulators, and is the MAC of choice in the evaluation of many higher-layer protocols for ad hoc networks. In addition, the IEEE 802.11 DCF contains various mechanisms and features upon which many of the recently-proposed MAC protocols rely, such as carrier sensing, collision avoidance, exponential backoff, and others. For these reasons, the study of energy consumption in the IEEE 802.11 DCF represents an important step towards the design of future energy-efficient protocols.

This paper presents advances in two fundamental aspects of energy-aware protocols: it introduces an analytical model to predict energy consumption in single-hop IEEE 802.11 ad hoc networks (under ideal channel conditions), and it validates this model with discrete-event simulations using Qualnet v3.6 [4], for which an extended and improved energy consumption accounting was implemented [5]. In particular, we are interested in addressing the following questions: (1) How accurate is the analytical model compared to discrete-event simulations? (2) What is the relative energy consumption among the MAC operational modes (e.g., transmit, receive, idle, etc) when nodes are actively contending for channel access (under saturation)? (3) What is the efficiency (Joule/Bit) incurred at each node for a specific network size? (4) How does the efficiency behave as the network size increases? (5) What is the impact of payload size on energy consumption, as the number of nodes increases?

Section II presents a brief overview of relevant work in energy consumption in the recent past. Section III presents the analytical model based on service time characterization. Following that, Section IV validates the model by comparing its results against data obtained using packet-level simulations. Finally, Section V presents our conclusions.

II. Related Work

A number of papers have characterized energy consumption in the IEEE 802.11 DCF. Stemm and Katz [1] have measured the power consumption of some NICs when used by different end-user devices. They also report on transport- and application-level strategies to reduce the burden of energy consumption at NICs. Feeney and Nilsson [2] have reported detailed energy consumption measurements of some commercially-available IEEE 802.11 NICs operating in ad hoc mode. Along the same lines, Ebert et. al. [6], [7] have measured the impact of transmission rate, transmit power, and packet size on energy consumption in a typical wireless network interface. In all previous works, however, the focus was on characterizing energy consumption during the many modes of operation of a NIC, under extremely simple scenarios: only two nodes operating in ad hoc mode, with one node acting as the sender and the other as the receiver. None of the efforts investigated the energy consumption that is drained from the MAC operation itself, i.e., *when nodes need to contend for channel access*. Such studies, as pointed out by Feeney [2],

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are difficult to reproduce experimentally, and discrete-event simulations or probabilistic analysis are more appropriate.

The modeling of energy consumption at the MAC layer has already been treated previously in the context of cellular networks. Chockalingam and Zorzi [8] have developed an analytical framework to study the energy efficiency of MAC schemes whose operations can be described by finite state-space Markov chains. In particular, they have compared different versions of a hybrid protocol using slotted ALOHA and reservation concepts, and evaluated their performance with respect to the fading characteristics of the wireless channel. Within the same context, Chen et. al. [9] have conducted an energy consumption analysis of some MAC protocols, including the IEEE 802.11 itself. They showed that MAC protocols that aim to reduce the number of contentions perform better from an energy consumption perspective. As far as the modeling of the IEEE 802.11 is concerned, however, their approach falls short in providing an accurate description of 802.11 DCF's behavior, because it ignores the binary exponential backoff operation, which is at the heart of the protocol. Instead, retransmissions and newly-generated packets are treated collectively as a single Poisson process. Moreover, because the analysis targets the infrastructure (WLAN) mode, the energy that is consumed when nodes act as *receivers* is not taken into account and, therefore, the model is not appropriate for an analysis of energy consumption in ad hoc networks, even fully-connected ones.

Qiao et. al. [10] explored power-conserving strategies for IEEE 802.11a/h systems that adaptively select appropriate power-rate settings for each data transmission attempt. Their approach is based on an off-line computation of a lookup table that contains power-rate combinations indexed by the data transmission status (frame retry counts, payload, etc.). To compute the lookup table, an energy consumption analysis of the MAC operation was developed, and a recursive calculation of the average total energy consumption was provided. However, because the goal of their analysis was the generation of the lookup table—not the analysis of the IEEE 802.11 itself—the account of energy consumption was built from the standpoint of a *sending* node and, again, the model is not suitable for the analysis of an ad hoc network as a whole, where nodes can play both the *sender* and *receiver* roles. Additionally, a more careful analysis of the events that happen during the times the backoff counter is frozen is lacking, and an upper bound was obtained instead for the energy spent during those periods.

Recently, Gobriel et. al [11] have investigated the effect of transmission power control on overall throughput and energy savings in power-aware ad hoc networks. The drawback of their analysis, which targeted the IEEE 802.11 DCF, is the fact that the binary exponential backoff algorithm is ignored and a *constant* contention window size is assumed instead. For this reason, as far as energy consumption is concerned, this model is not a good candidate to accurately reflect the energy consumption in IEEE 802.11 ad hoc networks. In addition, because the model was not validated/compared with discrete-event simulations, the accuracy of the model itself demands more study.

III. Energy-Aware Model

Typically, the various tasks performed by a MAC protocol correspond to different radio modes, which exhibit different power requirements. In the particular case of the IEEE 802.11 DCF, two power management mechanisms are supported: *active* and *power-saving* (PS) [3]. In this paper, we only consider the *active* mechanism, in which a node may be in one of three different radio modes, namely, *transmit*, *receive*, and *idle* modes. In an ad hoc network under saturation conditions, each node actively contends for channel access while at the same time is a potential receiver of some other node's transmission. Therefore, while attempting to transmit its *own* data frame, each node needs to respond to transmission requests from other nodes. Consequently, understanding the service time in a network under saturation conditions is fundamental, because nodes have to constantly switch to different power modes according to the perceived state of the channel and their own operation.

Recently, we have introduced an analytical model to characterize the service time of a node in a saturated IEEE 802.11 ad hoc network under ideal channel conditions (e.g., ignoring capture effects, hidden terminals, modulation and encoding schemes, etc.) [12]. In this paper, we briefly review this model and extend it to include a more realistic approach regarding the IEEE 802.11 binary exponential backoff algorithm. Following that, we present our energy consumption model, which is based on the service time characterization.

A. Service Time Model

In [12], we have derived closed-form expressions for the first two moments of a node's service time as a function of the channel state as perceived by each node. In the model, the channel state is conveyed in the form of *channel state probabilities*, and is expressed in terms of three mutually exclusive events: $E_i = \{\text{idle channel}\}$, $E_c = \{\text{collision}\}$, and $E_s = \{\text{successful transmission}\}$, which are the three events that dominate the behavior of the binary exponential backoff algorithm in the IEEE 802.11. The channel state probabilities were found based on the model introduced by Bianchi [13], where a nonlinear system of equations relates the steady-state probability that a node transmits a packet at any given time with the respective packet collision probability (for the specific case of a fully-connected network under ideal channel conditions).

The average service time can be decomposed in two parts: the time a node spends in backoff, and the time it takes to actually transmit the frame, as a result of a successful handshake with its intended receiver. For the average backoff time $\overline{T}_B$, we have found that

$$\overline{T}_B = \frac{\alpha(W_{\min}\beta - 1)}{2q} + \frac{(1-q)}{q}\, t_c, \tag{1}$$

where $\beta = [q - 2^m(1-q)^{m+1}]/(2q-1)$, $W_{\min}$ is the minimum contention window size specified for the backoff operation, m

is the standard-defined maximum power used to set up the maximum contention window size, (i.e., $W_{\max} = 2^m W_{\min}$), q is the conditional probability of a successful handshake (assumed constant), and $\alpha = \sigma p_i + t_c p_c + t_s p_s$, (where $p_i = P\{E_i\}$, $p_c = P\{E_c\}$, and $p_s = P\{E_s\}$ are the channel state probabilities that a node perceives during its backoff operation, with σ, t_c, and t_s being their corresponding average time duration). Given the backoff time characterization, the *average service time* ($\overline{T}$) is given by

$$\overline{T} = \overline{T}_B + \overline{T}_s, \tag{2}$$

where $\overline{T_s}$ is the average time to successfully transmit a packet at the end of the backoff operation (dependent on the packet size). In this paper, we assume that nodes communicate through the four-way handshake mechanism supported by the standard (the so-called "RTS/CTS" handshake) [3]. In this case, the time intervals t_s and t_c are given by

$$\begin{aligned} t_s &= \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \text{H} + E\{P\} + \\ &\quad + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta, \\ t_c &= \text{RTS} + \text{DIFS} + \delta, \end{aligned} \tag{3}$$

where RTS, CTS, and ACK are the times to transmit each of the control frames, SIFS and DIFS are the standard-defined time intervals corresponding to the *short interframe space* and the *distributed interframe space*, δ is the propagation delay, H is the time to transmit the packet header, and $E\{P\}$ is the time to transmit the average payload size. The value of $\overline{T}_s$ in Eq. (2) is simply $t_s -$ DIFS.

Although simple to compute, one of the drawbacks of our earlier model is the fact that frames are allowed to backoff *infinitely* in time. This is not consistent with what is defined in the standard, where retransmission counters limit the number of attempts to transmit a particular data frame, after which the frame is dropped. The infinite backoff abstraction makes the model much more tractable, but makes it too conservative, predicting higher service times (and consequently, lower throughputs) than what actually happens in the IEEE 802.11 DCF [12].

One contribution of this paper is to develop the average service time for the case of a *finite* backoff operation. For this purpose, we keep our assumption that the conditional probability of a successful handshake per transmission attempt, q, is constant. In other words, at the end of a backoff stage, the probability of a successful handshake is constant, regardless of the number of previous attempts. Now, let M be the maximum number of times a frame can be retransmitted, i.e., the maximum number of backoff stages a frame can undergo (defined in the standard). In this case, following the development in [12], and noticing that we now have a *truncate geometric distribution*, given by

$$P\{B = k\} = \frac{(1-q)^{k-1} q}{1-(1-q)^M}, \quad k = 1, 2, \ldots, M, \tag{4}$$

the average service time is now given by (omitting intermediate steps, which are straigthforward but tedious):

$$\overline{T}_B = \frac{\alpha W_{\min}}{2}\beta_1 - \frac{\alpha}{2}\beta_2 + \beta_3\, t_c, \tag{5}$$

where

$$\begin{aligned} &\beta_1 = \tfrac{A_1+A_2+A_3}{1-(1-q)^M}, \quad A_1 = \tfrac{2q\{1-[2(1-q)]^m\}}{2q-1} - 1 + (1-q)^m \\ &A_2 = \left(2^{m+1}-1\right)(1-q)^m \left[1-(1-q)^{M-m}\right] \\ &A_3 = \tfrac{2^m\left\{(1-q)^{m+1} - (1-q)^M[1+q(M-m-1)]\right\}}{q} \\ &\beta_2 = \tfrac{1-(1-q)^M(1+qM)}{q[1-(1-q)^M]}, \quad \beta_3 = \tfrac{(1-q)-(1-q)^M[1+q(M-1)]}{q[1-(1-q)^M]}, \end{aligned}$$

where the parameters α, m, $W_{\min}$, and t_c are defined as before. Because we are dealing with a saturated network under ideal channel conditions, the computation of the channel state probabilities p_i, p_s, and p_c follow the derivations in [12].

B. Energy Consumption Model

To account for the energy consumption under saturation conditions, we need to consider the many events that take place while a node is trying to transmit its own data frame. For this purpose, let us first look at Eq. (5), which describes the average time a node spends in backoff. As described in Section III-A, decrementing a node's backoff time counter depends on the node's perception of the *channel state*. As we have pointed out, there are three main channel states (or "events" during backoff): *successful transmission*, *collision*, and *idle channel* states. Notice that, these "states" do not correspond to the "modes of operation" of a network interface.

In the *successful transmission channel state*, the node in backoff experiences a successful transmission happening over the channel. This transmission, however, can either refer to a successful transmission between any two nodes in the network, or to a successful transmission having the node itself as the target receiver. In the former case, the node in backoff overhears an RTS and updates its network allocation vector (NAV) accordingly [3], freezing its backoff time counter for the duration of someone's else four-way handshake (or two-way handshake if the basic access mode is used). Notice that, in this case, the node in backoff first *overhears* the RTS and then stays *idle* for the duration of the advertised transfer, as recorded in the NAV. In the latter case, i.e., when the node itself is the recipient of the transfer, it has to *receive* the RTS and DATA frames from the sender, and *transmit* the corresponding CTS and ACK frames back to the sender. Meanwhile, power is also consumed during the time intervals corresponding to SIFS's, DIFS's, and propagation delays δ, during which the node stays *idle* or *senses* the channel[1].

In the *collision channel state*, similar events can take place from the standpoint of the node in backoff, i.e., the node is either overhearing or being the target of a transmission. Here, however, the node in backoff is overhearing an unsuccessful

[1]In reality, some power is also consumed when the network interface switches from one mode to another as, for instance, from the *receive* mode to the *transmit* mode (or *idle* mode). In this paper, we disregard the power costs of switching from one mode to another.

transmission or is being the target of a failed handshake. As before, energy is consumed while in overhearing and receiving modes, respectively. Nodes also consume power during the DIFS interval as the node waits before resuming its own backoff operation, after overhearing/receiving a failed handshake. Finally, during the *idle channel state*, the node in backoff basically *senses* the channel and decrements its backoff time counter each time no activity is detected for the duration of a time slot [3], [12].

All these three states correspond to times when the node is in backoff, perceiving the channel activity, and before attempting its own handshake, i.e., during the course of a backoff stage, as mentioned in Section III-A. The node attempts to establish a handshake with its intended receiver only at the end of a backoff stage. Each time the handshake fails, the node backs off again and repeats the process, until it finally succeeds in establishing the handshake and before it reaches the maximum number of allowed retransmissions, in which case, it drops its current data frame. In each of its handshake attempts, the node waits for a `cts_timeout` period before deciding that its RTS was not successful. In our analytical model (Eq. (5)), this collision resolution period is indicated by t_c, which, as described in Eq. (3), includes the time to *transmit* the RTS frame. Therefore, from Eq. (3), DIFS $+\ \delta$ seconds are spent in *sensing* the channel, waiting for the CTS frame that is never received.

During a successful four-way handshake with the node's intended receiver, the NIC switches through a number of modes of operation. During the four-way handshake time interval $\overline{T}_s$ (i.e., $t_s - \text{DIFS}$), the node *transmits* an RTS and a DATA frame (expressed in Eq. (3) by the header H and payload P), *receives* the CTS and ACK back from the receiver, and *stays idle* during the time intervals corresponding to SIFSs and propagation delays δ. According to experimental results reported by Feeney et. al. [2], the costs of *overhearing* a frame, staying *idle*, or *sensing* the channel are only marginally different from the cost of actually *receiving* a frame (in the IEEE 802.11 network interfaces evaluated). Note that these costs are not provided by manufacturers in data sheets. They were all measured in experiments. For this reason, many network simulators assume (implicitly or explicitly) the same power level for the *idle*, *overhear*, *sense*, and *receive* modes [4]. Consequently, because we want to compare our analytical model with simulation results, we follow this same assumption and consider two power levels only: *passive*, or P_{pas}, for the cases when the NIC is in any of the four aforementioned modes, and *active*, or P_{act}, for the mode in which the NIC is actually transmitting something. Given these considerations, all we need to do is to account for the time intervals in which the network interface stays either in the "passive" or "active" modes.

From our previous remarks, a node will be in "passive" mode during backoff except for the case when it is the target receiver of a handshake request, in which case it has to transmit CTS and ACK frames back to the sender. If we denote by T_{pas}^{back} the time a node is in *passive* mode during its backoff, we have, from Eq. (5),

$$T_{pas}^{back} = \frac{\alpha(W_{\min}\beta_1 - \beta_2)}{2}. \qquad (6)$$

At the end of a backoff stage, the node attempts to perform a handshake with its intended receiver. Before succeeding in doing that, however, the node will spend $\beta_3 t_c$ seconds, on average, in collision resolutions due to unsuccessful attempts (as shown in Eq. (5)). In each collision resolution time interval t_c, the node spends $\text{DIFS} + \delta$ seconds in "passive" mode. Hence, if $T_{pas}^{col\_res}$ denotes the average time spent in passive mode during collision resolutions and, likewise, $T_{act}^{col\_res}$ the average time spent on "active" mode during collision resolution, we have that

$$T_{pas}^{col\_res} = \beta_3(\text{DIFS} + \delta) \quad \text{and} \quad T_{act}^{col\_res} = \beta_3 \text{RTS}. \qquad (7)$$

When the node succeeds in performing a handshake, it will spend $T_{pas}^{4\text{-}way}$ seconds in passive mode during the four-way handshake. From Eq. (3), this time interval corresponds to

$$T_{pas}^{4\text{-}way} = \text{CTS} + \text{ACK} + 3 \times \text{SIFS} + 4\delta, \qquad (8)$$

whereas in transmission the node will spend

$$T_{act}^{4\text{-}way} = \text{RTS} + \text{H} + E\{P\}. \qquad (9)$$

Finally, we need to take into account the case when the node is the target receiver of a handshake request during its backoff, in which case it needs to transmit CTS and ACK frames back to the sender. In a single-hop ad hoc network under ideal channel conditions, no capture or hidden terminal problems happen. Therefore, it is always assumed that all frame collisions are due to RTS collisions *at the intended receiver*. This means that, under such assumptions, *no CTS or ACK frame is ever transmitted unsuccessfully*. Therefore, the recipient of a handshake request only transmits a single CTS and a single ACK frame for each data transmission request, i.e., only those frames corresponding to the completion of a successful handshake. Furthermore, assuming a balanced and fair distribution of load in the network [2], if T_{total} denotes the total observation time, then, on average, $T_{total}/\overline{T}$ data frames will be received by any node during the time interval T_{total}. From the remarks, for each data frame transmitted successfully, there is one and only one CTS and ACK frame sent by the intended receiver. Therefore, the average time T_{act}^{back} a node spends transmitting CTS and ACK frames back to other nodes (while the node itself is in backoff) is given by

$$T_{act}^{back} = \overline{N}(\text{CTS} + \text{ACK}), \qquad (10)$$

where $\overline{N} = T_{total}/\overline{T}$ is the average number of data frames transmitted over the interval T_{total}. Hence, if $\mathcal{E}_{passive}$ and $\mathcal{E}_{active}$ denote the energy consumptions in the *passive* and

[2]This assumption is realistic in ad hoc network scenarios such as n-way conferencing, and sensor network monitoring. Motivated by applications that may produce non-uniform traffic distributions, one of our directions of future work is to extend our model accordingly.

active modes, respectively, during the observation time T_{total}, then, from above,

$$\mathcal{E}_{passive} = \overline{N} P_{pas} \left(T_{pas}^{back} + T_{pas}^{col\_res} + T_{pas}^{4\_way} \right), \quad (11)$$

$$\mathcal{E}_{active} = \overline{N} P_{act} \left(T_{act}^{back} \overline{N}^{-1} + T_{act}^{col\_res} + T_{act}^{4\_way} \right), \quad (12)$$

where the $\overline{N}^{-1}$ accounts for the $\overline{N}$ already included in T_{act}^{back}. Finally, the total energy consumption $\mathcal{E}_{total}$ is simply

$$\mathcal{E}_{total} = \mathcal{E}_{passive} + \mathcal{E}_{active}. \quad (13)$$

IV. Model Validation and Performance Analysis

We validate our energy-aware model through packet-level simulations using the Qualnet v3.6 simulator [4] with improved energy consumption instrumentation [5]. We then use the model to account for energy consumption of saturated IEEE 802.11 single-hop ad hoc networks in a variety of ad hoc scenarios with different network- and payload sizes. Results correspond to the average of 10 runs with different seeds and different transmission start times (necessary to reduce IEEE802.11 unfairness). Table I summarizes the simulation parameters used. It is important to note that simulation parameters were chosen in order to provide a simulation environment as close as possible to the assumptions made in our model.

Parameter	Value	Parameter	Value
Area	50 × 50 m	Phy model	phy-IEEE802.11
Number of nodes	10, 20, 30, 40, 50	RX model	SNR-based
Node placement	random	PHY-RX-SNR-THRESHOLD	10.0
Node mobility	none	Routing protocol	static
Simulation time	300 sec	Traffic	CBR
Bandwidth	1 Mbps	Payload size	20 and 1472 bytes
TX-POWER	10 dBm	Packet interval	0.024 sec
RX-POWER	-82.045 dBm	Power consumption in TX	1650 mW
Path loss model	free-space	Power consumption in RX	1400 mW
Fading model	none		

TABLE I

SIMULATION PARAMETERS

Figures 1(a) and 1(b) show the average energy consumption per node (in Joules) for the *active* and *passive* modes, as well as their sum (i.e., the total energy consumption) for different network sizes. Figure 1(a) plots results for the 1472-byte payload, whereas Figure 1(b) shows the results for a payload of 20-bytes. As we can observe, the analytical model predicts quite well the simulation results. Because the analytical model is more conservative in terms of throughput [12], it leads to slightly smaller energy consumption values for the *active* mode and, consequently, slightly bigger values for the *passive* mode, compared to simulations. It is worth mentioning that, when compared to the model, Qualnet simulations use more "realistic" PHY-layer parameters, as shown in Table I. Despite this fact, the analytical model proved to be a good abstraction of the simulated scenarios, supporting our earlier assumptions of restricting collisions to RTS frames only (for fully-connected networks).

Regarding individual contributions of the operational modes to overall energy consumption, the *passive* mode is responsible for the largest fraction of the total energy consumed. For the network sizes investigated, the *passive* mode consumes more than 88% of the total energy drained (for the chosen parameters). This result is a direct consequence of the fact that, under saturation and high contention, nodes spend most of their time backing off and listening to the channel, instead of actually transmitting data. For all network sizes investigated, the average total energy consumption is about 420 J, leading to an average power consumption of 1.4 W for the 300 s period, i.e., equivalent to the nominal power setting for the passive modes (energy consumption in RX) as shown in Table I. This is consistent with the observation that passive modes are responsible for most of the energy dissipated. As the number of nodes increases, the power consumption in *passive* mode increases from 1.25 W up to 1.37 W. In other words, although the nominal value for the *transmit* (active) mode is 250 mW higher than the value for the *receive* (passive) mode, its impact is practically insignificant as far as the MAC operation in saturation conditions is concerned. This result opposes the findings in [2] and [6] which, under the perspective of a two-node scenario (sender/receiver) without contention, transmit mode is the largest overall energy consumer.

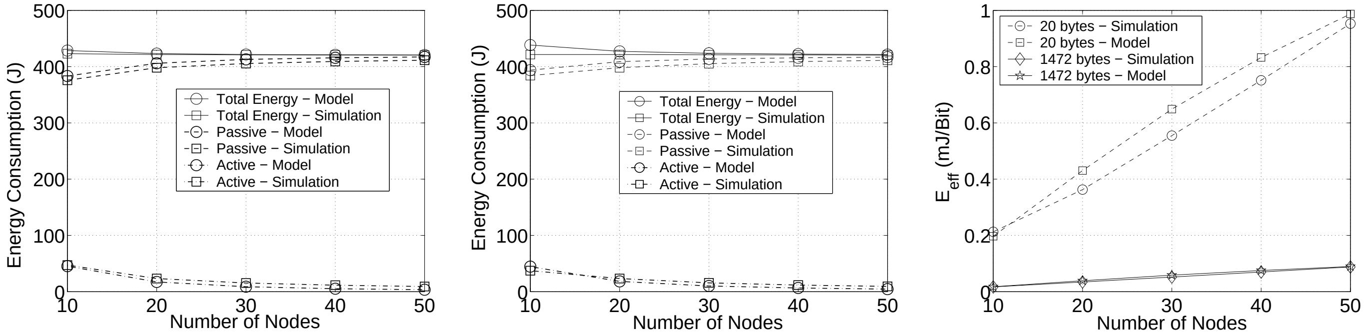
In cases where power-saving methods cannot be employed for some reason (like the IEEE 802.11 power saving (PS) mode [3], not available at some NICs), this result suggests that one can design energy-efficient WLAN devices by focusing on the optimization of circuits that are mainly active during *passive* modes of operation (see [10] for a simplified block diagram of a WLAN device). In fact, in typical WLAN devices, the RF power amplifier is a key component that, alone, demands most of the nominal power consumption, and it is used only in the transmit mode [6], [10]. According to our results, this is exactly the component that will *affect performance the least*, as far as energy consumption under channel contention is concerned.

Another interesting observation from Figures 1(a) and (b) is that the energy spent on both 20- and 1472-byte transfers are equivalent in all modes of operation. In other words, from the standpoint of energy-efficiency, it is better to transmit bigger payloads than smaller payloads, because the net energy consumption is the same. This last result can be better illustrated by the *energy efficiency to transmit useful data*, E_{eff} given by

$$E_{\text{eff}} = \frac{\text{Total Power Consumption}}{\text{Goodput}} \ \frac{\text{J}/s}{\text{Bit}/s}. \quad (14)$$

Figure 1(c) shows the behavior of E_{eff} for the cases of 20- and 1472-byte data payloads as the number of nodes increases. Surprisingly, the energy cost appears to have an *almost linear* increase with network size. Moreover, the energy cost to transmit a 20-byte data payload grows at a rate that is about one order of magnitude higher than the cost to transmit a 1472-byte payload. For the 1472-byte scenario, the energy cost grows at a rate of approximately 0.002 mJ/Bit, whereas in the 20-byte scenario, the energy cost grows at 0.02 mJ/Bit.

The usefulness of an analytical model such as the one we provide here is the ability to provide quick answers without resorting to simulations. As an example, we use it to analyze the energy consumption of commercially-available NICs, namely the Lucent WaveLan card transmitting at both



(a) (b) (c)

Fig. 1. (a) Per-node average energy consumption versus network size for a 1472-byte payload. (b) Per-node average energy consumption versus network size for a 20-byte payload. (c) Energy efficiency per bit versus network size for 20-byte and 1472-byte payloads.

1 Mbps (TX = 1650 mW and RX = 1400 mW) and 11 Mbps (TX = 1400 mW and RX = 900 mW), and the Cisco Aironet PC4800 at 1 Mbps (TX = 2200 mW and RX = 1350 mW) [6]. Figure 2 shows that, as expected, the power setting that provides the smallest energy consumption is exactly the one with the smallest power level in *passive* mode, i.e, the 11-Mbps WaveLan. Another interesting result is the little impact that transmit power has on overall results. All three settings showed similar performance in active mode, despite their relative nominal power differences.

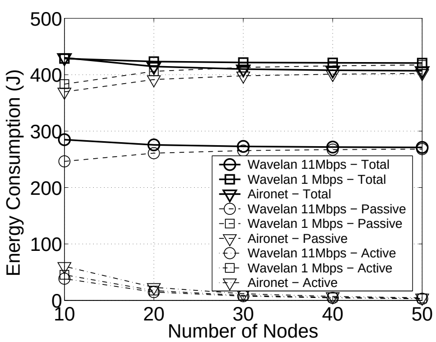


Fig. 2. Energy consumption from the analytical model for different power settings.

V. Conclusions

In this paper, we have introduced a simple analytical model to predict energy consumption in saturated IEEE 802.11 single-hop ad hoc networks under ideal channel conditions. In contrast to all previous work that has focused on power consumption of IEEE 802.11 NICs without any channel contention, the opposite case was investigated here, with nodes actively contending for channel access under saturation conditions. In that case, the *passive* modes of the MAC operation dominate the energy consumption, whereas the *active* mode has just marginal impact (even when different power settings were used). Moreover, we have found that the energy cost to transmit useful data grows almost linearly with thenetwork size, and that the transmission of large data payloads is more advantageous from the standpoint of energy consumption under saturation conditions. Our future work will address PHY-layer aspects [14], extending this work to non-saturated, non-balanced multihop ad hoc networks, and MAC protocols for sensor networks.

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